(54) Title: EXTENDED-RANGE MOIRE CONTOURING

(57) Abstract

The measurement range of Moire contouring techniques is extended beyond the Nyquist frequency limit by constraining the reconstruction of a surface contour according to a priori knowledge about the surface. In one example, the a priori knowledge is that the surface is smooth, being described by a function having continuous derivatives, and the location of a region where the surface changes by less than C/2 per sample. In another example, the a priori knowledge is the location and height of a step discontinuity to within C/2, where C is the contour interval.

EXTENDED-RANGE MOIRE CONTOURING
Technical Field

This invention relates to the field of surface contour measurement, and more particularly to
5   Moire contouring techniques.
Background Art

Three-dimensional surface contouring using Moire techniques is well known (see for example U.S. Patent No. 4,212,073 issued July 8, 1980 to
10 Balasubramanian). There are two basic implementations of this technique: Moire topography and Moire deflectometry. Moire topography is used to measure surfaces that are diffuse reflectors. Moire deflectometry is used with surfaces that are specular
15 reflectors. The type of data that is collected with either of these techniques is similar and requires similar processing.

An example of a system used for Moire topography is shown in Fig. 1. Parallel equispaced
20 lines of light or fringes 10 having a period d are formed for example by projecting the image of a grating 18 onto a surface 12 to be measured. The scattered intensity is viewed at an angle θ from the direction of the fringe projection by a lens 14
25 and camera 16 having an image sensor 17. If the surface 12 is not flat, a curved fringe pattern is seen, and the curvature is related to the surface profile. The intensity pattern on the surface is given by:

30 $i(x,y)=i'(x,y)+i''(x,y)\cos[(2\pi/d)(x+h(x,y)\tan\theta)]$,   (1)
where $i'(x,y)$ and $i''(x,y)$ are constants relating to the DC bias and AC modulation of the viewed fringes, d is the period of the projected fringes on the surface, $h(x,y)$ is the surface height profile, and
35 the fringes are projected parallel to the y-axis. Only the fundamental frequency component of the projected grating 18 is given by this equation — — if

the original grating is a square—wave target, for
example a Ronchi ruling, higher frequency terms will
appear in equation (1). The information about the
surface height in the viewed fringe pattern is
5   encoded in the spacing of the fringes. The surface
height difference needed to increase or decrease the
period of the viewed fringes by the base fringe
period d is known as the contour interval C, where

$$C = d/\tan\theta \ . \qquad\qquad (2)$$

10   There are at least two method for producing
the projected fringes. The first is an optical
projector as shown in Fig. 1. The grating
transparency 18 is illuminated by a light source 20
and is imaged onto the surface 12 by the lens 22. To
15   eliminate magnification errors with depth of field, a
telecentric lens system is often used. However,
projectors which produce diverging fringe patterns
are also used, and the analysis is more complicated.
In that event, the contour interval C is not a
20   constant and changes as a function of height and
position. Parallel, equispaced fringes are assumed
for this analysis. The second method for projecting
fringes is to use an interferometer as shown in Fig.
2. The interferometer is in a Twyman—Green
25   configuration. A beam of collimated laser light 26
is split into the two arms of the interferometer by
the beamsplitter 28, and parallel equispaced fringes
30 are produced by interference when the two beams
are recombined. The period of the fringes can be
30   changed by tilting one of the two mirrors 32.

The fringe pattern is sampled by the image
sensor 17, and the sampled values are supplied to a
computer 33. The computer 33 processes the samples,
and displays the processed samples on a display, such
35   as a CRT 35. A standard keyboard 37 is employed to
input information into the computer to control the
Moire contouring apparatus.

The other implementation of Moire contouring
is Moire deflectometry. An example of such a system
is shown in Fig. 3. As diagramed, a collimated input
beam 38 is reflected off a specularly reflecting
5 surface 40 at an angle α. The reflected beam
passes through a grating 42 (having a pitch d) and
impinges on a detector 44 that is a distance A from
the grating. A surface deformation 46 having a slope
of β will deflect the reflected beam through an
10 angle of 2β. A distorted shadow of the grating 42
falls on the detector 44. The displacement of the
fringe at a given location will be a function of the
local deviation angle β, and the displacement
approximates 2βA. In this situation, the contour
15 interval C_D occurs when this displacement is equal
to the grating period d:

$$C_D = d/2A . \qquad (3)$$

Note that the contour interval is an angle, not a
distance. In addition to the differences in the
20 surface reflectivities, this condition marks the
major difference between Moire topography and
deflectometry. Moire deflectometry measures the
slope of the surface perpendicular to the grating
lines, while Moire topography gives the surface
25 height distribution.

Without loss of generality, the majority of
the remainder of the discussion will center on the
application of Moire topography. It should be clear,
however, that the principles described here are
30 equally applicable to Moire deflectometry.

There are several schemes available for
detecting and measuring the curvature of the viewed
fringe pattern. One scheme involves viewing the
pattern through a second grating, identical to the
35 projection grating, that is located in the focal
plane of the camera 16. A Moire or product of the
distorted test pattern and the reference pattern is

—4—

formed, hence the name Moire topography. When the
grids are chosen to be identical, a flat object will
produce a zero-frequency beat or difference
frequency. The resulting Moire pattern will have no
5   fringes in it after the high spatial frequencies
corresponding to the individual gratings are filtered
out. When the surface is not flat, low frequency
Moire fringes, corresponding to the difference
between the reference and test patterns, will appear
10   in the filtered output. The Moire pattern is
sampled, and the fringe centers are located. The
surface profile can then be constructed by using the
fact that adjacent Moire fringes indicate a change of
the surface height of one contour interval C.
15   An often more convenient method of sampling
the Moire pattern is to image the distorted test
pattern directly onto a solid-state detector array.
The spacing of the pixels themselves in the array
will serve as the reference grid, and the phenomenon
20   of aliasing will result in the low frequency Moire
pattern, which is the product of the reference
grating (i.e. the sensing array) and the deformed
projected grating pattern. To simplify the analysis,
all dimensions will be discussed as they appear in
25   the sensor plane. For example, scale factors
relating to the magnifications of the imaging systems
will be ignored.
        For the purpose of modeling the system, the
sensor geometry diagramed in Fig. 4 is assumed. A
30   rectangular array of rectangular pixels 48 is used,
and the pixels have dimensions and spacings of a by b
and x_s by y_s respectively. The sampled image
$i_s(x,y)$ produced by the sensor is
$$i_s(x,y)=[i(x,y)**rect(x/a,\ y/b)]comb(x/x_s,y/y_s),\qquad (4)$$
35   where $i(x,y)$ is the viewed fringe pattern as
described by equation (1), ** indicates a
two-dimensional convolution, and the comb function is

an array of delta functions with spacing of x_s by
y_s. The frequency space representation of the
sampled pattern is obtained by taking a Fourier
transform:

5      $$I_s(\xi,\eta)=[I(\xi,\eta)sinc(a\xi,b\eta)]**comb(x_s\xi,y_s\eta), \qquad (5)$$

where ξ and η are the spatial frequency
coordinates, $I(\xi,\eta)$ is the spectrum of the
intensity pattern, and

$$sinc(a\xi,b\eta)=\frac{sin(\pi a\xi)}{\pi a\xi} \cdot \frac{sin(\pi b\eta)}{\pi b\eta} . \qquad (6)$$

10

The active area of the pixel, represented by the rect
and sinc functions in equations (4) and (5), serves
to reduce the contrast of the recorded fringe
pattern. The intensity pattern is averaged over the

15   pixel, and the contrast of a fringe at a particular
spatial frequency or spacing is reduced by the
corresponding value of the sinc function.

The nature of the previously mentioned
aliasing and the limitations in measurement range of

20   the conventional Moire techniques can be observed by
plotting equation (5) in one dimension for two
different types of viewed patterns. The product
$I(\xi)sinc(a\xi)$, which is the input scene, is shown
in Fig. 5a. A sinusoidal fringe pattern is assumed,

25   and this product contains three portions – – the DC
bias at zero frequency 50 and two lobes 52 centered
around the frequencies $\pm$ 1/d. These lobes contain
the information about the curvature and spacing of
the fringe pattern. Since a pattern of frequency 1/d

30   is projected, one would expect the spectral content
of the viewed pattern to be centered at these
frequencies. The maximum width of these lobes is
denoted W, and it is not necessary that W be centered
on the frequency 1/d.

35   Before proceeding, it is useful to define a
few terms. The Nyquist frequency f_N of a sensor is
defined to be half the sampling frequency of the

sensor, or $1/2x_s$. This frequency is generally
considered to be the limiting resolution of a sampled
imaging system. The baseband of the sensor is the
frequency range near the origin between $\pm f_N$. A
5   Moire interval has been defined for this application
as a frequency band of width f_N that begins (and
ends) at a multiple of the Nyquist frequency.

The first object to consider is one which is
close to being flat. In this case, the width W is
10   less than f_N, and the proper choice of d will place
the sidelobe of the viewed pattern in the second
Moire interval, at frequencies between f_N and
$1/x_s$. The sampling operation replicates this
spectrum at the multiples of the sampling frequency
15   (equation (5)), and this situation is shown in Fig.
5b. All of the replicated lobes are well separated,
and the first−order replicas 54 of the lobes have
been mapped into the baseband of the sensor. The
initial frequencies 56 in the viewed pattern,
20   centered at 1/d, are beyond the Nyquist frequency of
the sensor, and have been aliased to lower spatial
frequencies. This effect subtracts the reference
grid, the sensor sampling pattern, from the viewed
fringe pattern. Note that a viewed fringe occurring
25   at the same frequency as the samples is mapped back
to zero frequency − − the same result as when viewing
the pattern through a reference grating. Since the
orders are separated, the sampled spectrum can be
easily low−pass filtered to yield only the desired
30   information in the sensor baseband, the Moire fringes.

When the object is more steeply curved than
that represented in Fig. 5b, the range of frequencies
observed in the viewed intensity pattern will be
greater, and W will increase. If W is greater than
35   the Nyquist frequency, the sidelobe will no longer
fit into a Nyquist interval, and the resultant
spectrum of the sampled image is given in Fig. 5c.

The lobes overlap and can no longer be separated.   A
measured fringe frequency in the baseband cannot be
identified as having originated in just the first
order side lobe 58 as required for the Moire
5   analysis.   It may also be present in the baseband as
a result of the overlap of the other replicas 60.
Prior art methods of Moire analysis have not been
able to resolve this dilemma, and have failed to
properly reconstruct objects of this type.
10   The maximum measurement range of
conventional Moire topography can be calculated from
the foregoing analysis.   The maximum frequency
difference in the viewed fringes must be less than
the Nyquist frequency — — this frequency range must
15   fit into the baseband of the sensor.   The maximum
period of a Moire fringe must therefore be twice the
sample pitch of the sensor or a half fringe per
sample.   Since a contour interval corresponds to a
full fringe, the maximum surface change that is
20   allowed by this analysis is a half of a contour
interval per sample (C/2 per sample).   This
constraint limits the maximum slope of the surface
that is being measured and indirectly limits the
maximum excursion.
25   A method to obtain the relative phase of the
fringe pattern at each sample is to use synchronous
detection or phase-shifting techniques as disclosed
in the referenced U.S. Patent No. 4,212,073.
According to this method, an arbitrary phase shift is
30   inserted between the reference grid (the sensor) and
the viewed intensity pattern by laterally shifting
either the projection grating or the sensor.
Mechanisms for obtaining this phase shift are easy to
implement.   In Fig. 1, the projection grating 18 can
35   be translated by a transducer 24 in the direction of
arrow B to obtain the shift.   The interferometrically
produced pattern in Fig. 2 can be phase shifted by

translating either of the mirrors 32 in a direction
perpendicular to its surface. A piezoelectric
translator 34 is used for this purpose to move one of
the mirrors in the direction of arrow C. These

5   shifts can be computer controlled, with a
time—varying intensity pattern being produced.

      A general expression for the intensity
pattern that is viewed by the detector 17 for a
particular phase shift δ_n is

10   $$i_n(x,y)=i'(x,y)+i''(x,y)\cos[(2\pi/d)(x+h(x,y)\tan\theta - \delta_n)], \qquad (7)$$
where n indexes the phase shift, and the other terms
are as described in equation (1). The data set
needed for the analysis of the surface height using
phase—shifting techniques is a set of three or more

15   patterns recorded with different phase shifts
δ_n. A simple phase—shift algorithm to implement
is the four—step method, where the phase is advanced
in four equal steps of 90°. In this case,

$$\delta_n=0, \; d/4, \; d/2, \; 3d/4 . \qquad (8)$$

20   The four recorded intensity patterns after
trigonometric simplification are

$$i_1(x,y)=i'(x,y)+i''(x,y)\cos[(2\pi/d)(x+h(x,y)\tan\theta)]$$
$$i_2(x,y)=i'(x,y)+i''(x,y)\sin[(2\pi/d)(x+h(x,y)\tan\theta)] \qquad (9)$$
$$i_3(x,y)=i'(x,y)-i''(x,y)\cos[(2\pi/d)(x+h(x,y)\tan\theta)]$$

25   $$i_4(x,y)=i'(x,y)-i''(x,y)\sin[(2\pi/d)(x+h(x,y)\tan\theta)].$$
Combining these equations and solving for h(x,y)
gives the result

30   $$h(x,y)=(d/2\pi\tan\theta)\tan^{-1}\frac{i_2(x,y)-i_4(x,y)}{i_1(x,y)-i_3(x,y)} \; -x/\tan\theta. \qquad (10)$$

The last term in this equation is a linear tilt which
corresponds to the projected uniform fringe pattern.
This term is automatically removed by the Moire
process or the aliasing that occurs with the

35   solid—state sensor. Neither of these effects are
included in this equation, but the term can be safety
ignored. The term disappears when the reference

grating is subtracted from the viewed fringe
pattern. Noting also that $d/\tan\theta$ is equal to the
contour interval C, this equation can be rewritten as

5 $$h(x,y)=(C/2\pi)\tan^{-1}\frac{i_2(x,y)-i_4(x,y)}{i_1(x,y)-i_3(x,y)} \cdot \qquad (11)$$

This last equation is evaluated at every point on the
surface to yield a map of the surface height. If the
signs of the numerator and denominator of equation

10 (11) are determined, the arctangent can be calculated
over a range of 2π. The result of equation (11) is
therefore to assign a surface height to each sample
that is a number between zero and C, the contour
interval.

15   The next step in the analysis for Moire
topography leads to its limitation. The result of
the arctangent in equation (11) is to give the
surface height modulo C. Fig. 6 is a plot of an
actual surface profile 62 and the surface profile

20 modulo C 64 as would result from the above
calculation. In order for the data to be useful, the
discontinuities resulting from the arctangent must be
removed from the calculated profile 64. In other
words, the calculated surface height 64 returns to a

25 value of zero every time the actual surface height 62
equals a multiple of C, and this segmented or
"compressed" surface must be reassembled to obtain
the correct result. The procedure that is used in
Moire topography to remove these discontinuities is

30 to start at a single sample of the surface contour,
normally at the center of the surface, and to assume
that the height change between any two samples is
always less than C/2. If the surface height
difference calculated for two adjacent samples

35 exceeds C/2, then C is added to or subtracted from
the value of the second sample until the above
condition is met. The entire surface is then

-10-

reconstructed by working outward in this manner for the starting sample. Fig. 7 illustrates this process, where the original calculated surface height 66 is indicated by crosses, and the reconstructed
5   values 68 are noted by circles. A dashed line has been drawn through the reconstructed values.

As was noted above, for a proper reconstruction, the surface height must change by less than $C/2$ per sample. This method of measurement
10 therefore places a restriction on the types of surfaces that can be correctly measured. The slope of the surface must be less than $C/2$ per sample, and only surfaces that have small departures from a flat can be tested. For highly curved surfaces, the
15 surface height changes too rapidly for the reconstruction algorithm to keep up with it. Because of the arctangent, this constraint in reconstruction is often referred to as the 2π ambiguity problem.

Attempts by others to overcome this
20 limitation have basically fallen into two categories. First, the number of samples can be increased to widen the Moire intervals, or second, the projected fringe frequency can be decreased to increase the contour interval. However, since the
25 resolution of these systems is a fraction of a contour interval, often between $C/100$ and $C/1000$, this latter change will also decrease the absolute resolution of the system. The resolution of these systems is signal—to—noise ratio dependent and is
30 dictated by the errors in the arctangent calculation. Contributing factors include the number of bits in the digital computations and sensor noise.

Another detection scheme used in Moire topography is called spatial synchronous detection or
35 spatial heterodyne. According to this technique, the viewed fringe pattern is recorded and digitized at high spatial resolution, and the reference grid is

-11-

generated in the computer. The two patterns are then
multiplied, and the samples of the Moire fringes are
produced in the computer. The computer—generated
grid can also be shifted to yield a phase—shifting
5   technique similar to what has been described. The
trade—off between this technique and the temporal
phase—shifting approach is that more pixels are
needed in the sensor. An advantage is that only one
record of the test pattern is needed. The spatial
10   heterodyne technique does not require a mechanism to
shift the phase of a reference grating and is immune
to temporal variations such as vibration. Range
limitations, analogous to those described above,
exist for the spatial heterodyne technique. Spatial
15   heterodyne Moire topography is analogous to the
phase—shifting technique, where all the information
is sensed at once, and the samples of the Moire
pattern are generated in a computer.

        Accordingly, it is the object of the present
20   invention to extend the useful range of Moire
contouring past the Nyquist frequency limit of
conventional Moire contouring without increasing the
number of samples of the Moire pattern and/or without
increasing the projected fringe frequency.

25   <u>Disclosure of the Invention</u>

        The condition of Moire topography that
requires a surface to have no slopes greater than a
half contour interval per sample of the Moire pattern
in order to be properly measured has become an
30   accepted standard for these techniques. As will be
demonstrated, this limit is not fundamental and is
readily overcome by making simple and realistic
assumptions about the surface under test.

        As shown in Fig. 5c, steeply curved surfaces
35   lead to the overlap of several of the sidelobes of
the viewed fringe pattern spectrum in the baseband of
the sensor. One property of the viewed intensity

pattern is that at any location in the field, the
pattern can be described by a single local spatial
frequency, or at most by a very narrow range of
frequencies. Therefore, at any particular sample
5   location, a single spatial frequency ξ_m is
measured. Because of the overlap, this frequency may
also be associated with other spatial frequencies in
the overlapping sidelobes. The correct fringe
frequency ξ_o that corresponds to the actual
10 surface contour is one of the solutions to

$$\xi_o = |\xi_m \pm 2nf_N|, \quad n=0,1,2\ldots \quad . \quad (12)$$

The accepted analysis assumes that n=0. According to
the present invention, previously known information
about the surface is used to resolve this frequency
15 ambiguity problem without neccessarily restricting n
to equal zero.

The name given to this new technique for
analyzing Moire patterns based upon a priori
knowledge is Extended−Range Moire Topography.
20 According to the present invention, method and
apparatus for Moire contouring are provided whereby a
test pattern of lines formed having distortions
representing the contour of a surface to be
measured. Samples are formed of a Moire pattern
25 representing the product of the test pattern and an
undistorted reference pattern. The samples represent
the height of the surface contour modulo C, where C
is a function of the spacing of the lines of the test
pattern. The actual contour is reconstructed from
30 the samples by adding or subtracting multiples of C.
A constraint based upon a priori knowledge of the
surface contour is applied to the reconstruction to
correctly reconstruct the contour when the contour
changes by more than C/2 per sample. In one example
35 of the present invention, the a priori knowledge is
that the surface contour is smooth, therefore having
continuous derivatives, and the location of a

−13−

neighborhood on the surface where the contour changes by less than C/2 per sample. In another example, the a priori knowledge of the surface is the location and height of a step discontinuity to within less than C.

5 <u>Brief Description of the Drawings</u>

Fig. 1 is a schematic diagram of Moire topography apparatus useful with the present invention;

Fig. 2 is a schematic diagram illustrating

10 an alternative method for generating a line pattern;

Fig. 3 is a schematic diagram useful in describing Moire deflectometry for a specularly reflecting surface;

Fig. 4 is a schematic diagram illustrating a

15 sparse image sensing array according to the present invention;

Figs. 5a−c are frequency space diagrams useful in describing Moire topography;

Fig. 6 is a diagram illustrating an actual

20 surface contour, and the surface contour modulo C;

Fig. 7 is a diagram showing the reconstruction of an actual contour from a contour modulo C;

Fig. 8 is a graph of MTF vs. sampling

25 frequency useful in describing the operation of the present invention;

Figs. 9a−D are graphs of sample values useful in describdng the operation of the present invention;

30 Figs. 10a and b are diagrams illustrating the procedure for reconstructing a two−dimensional contour having continuous derivatives;

Fig. 11 is a flow chart showing the steps of reconstructing a surface contour according to the

35 present invention;

Fig. 12 is a diagram illustrating a Moire pattern produced at a step discontinuity in a surface;

-14-

Fig. 13 is a diagram useful in describing the application of the present invention to a step discontinuity; and

Fig. 14 is a diagram illustrating the application of the invention to a surface of a known design and known manufacturing tolerances.

Modes of Carrying Out the Invention

Two modes of carrying out the present invention will be described, one for smooth surfaces, and one for surfaces having step discontinuities. Although the modes will be described with particular reference to phase-shifting Moire topography, it will be readily apparent that the present invention may be applied to other forms of Moire contouring, such as heterodyne Moire topography, and Moire deflectometry.

Smooth Surfaces

As explained above, the results of the phase-shifting analysis does not give the absolute height profile, but rather the relative height modulo C. The actual surface is reconstructed if the proper number of C's are added to each sample of the Moire pattern.

The assumption used by conventional Moire topography to remove the discontinuities is that the surface is continuous − − it does not change by any more than a half fringe or C/2 per sample. According to the present invention, information is recovered from fringes not satisfying this condition by assuming that the surface under test is also smooth. Therefore, in addition to being continuous, the surface also has continuous derivatives.

The procedure for testing the surface begins with the standard Moire topography technique, including applying the surface continuity constraint, to obtain a first estimate of the actual contour of the surface. This result is then placed under the additional constraint that the slope of the surface

-15-

cannot change by more than C/2 per sample per sample
of the Moire pattern. The appropriate number of C's
are added to each sample to satisfy this condition,
and there is only a single solution which produces

5   this result. The first derivative continuity
constraint places a limit on the maximum allowable
second derivative of the surface. However, this
result is further corrected by requiring that the
second derivative of the surface is also continuous,

10   and adding more C's − − the third derivative is now
limited to variations of C/2 per sample per sample
per sample. This procedure can be continued to
higher order derivatives until a more fundamental
limit, as described below, is reached.

15   There is one other restriction on the
surface that is needed to implement this technique
for smooth surfaces. In order to calculate initial
values of the various surface derivatives, there must
be a small block of samples where the height of the

20   surface changes by less than C/2 per sample. A block
of 2 by 2 samples is needed to implement first-
derivative continuity, a 3 by 3 block is needed for
second-derivative continuity, etc. Actually, this
condition is slightly overstated. All that is

25   actually required for the nth derivative continuity
reconstruction is a block of n+1 by n+1 samples that
are correctly reconstructed by the previous order
reconstruction. A correct initial value of the
particular derivative must be available for the

30   reconstruction. This block of initial samples is
automatically identified by the computer, or an
operator identifies their location, and inputs the
location into the computer via keyboard 37, see
Fig. 1.

35   The image sensor used to record the viewed
fringe pattern that is preferable for implementing
the extended-range Moire topography for smooth

surfaces is one that is appropriate for imaging
spatial frequencies that are well above the Nyquist
frequency of the image sensor. The sensor must be
prone to alias. As indicated in equation (5), the
5   size of the active area of each pixel relative to the
pixel pitch determines the response of the pixel to a
particular spatial frequency input — — the pixel
MTF. If quantity G is defined as

$$G = a/x_s, \tag{13}$$

10   or the ratio of the pixel width to the pixel pitch,
the MTF of an individual pixel will be a sinc
function (of the form sin(x)/x) with its first zero
at a spatial frequency equal to the sensor sampling
frequency divided by G, $1/(Gx_s)$. Uniform response
15   across the pixel is assumed, and different values of
G are possible in the x and y directions. To have
the pixel cutoff frequency well beyond the Nyquist
frequency, small values of G are needed. A small
value of G implies that the pixels 48 on the sensor
20   17 (see Fig. 4) are small and widely separated. This
is referred to herein as a sparse array. Most
conventional sensors are designed for pictorial
sensing and to capture as much light as possible, and
therefore they have values of G generally between .5
25   and 1. The pixels on these sensors are almost
contiguous. A comparison of the pixel MTF's of a
standard sensor 70 and a sparse—array sensor 72 is
given in Fig. 8. For purposes of the present
description, a sparse array is defined as an array
30   where G is less than .5.

       The pixel cutoff frequency occurs at the
spatial frequency corresponding to the condition of a
full viewed fringe period fitting exactly inside a
pixel. At this point the sensor is blind to the
35   input, as a lateral shift of the fringe pattern will
not change the signal. This point defines the
ultimate limiting range of extended—range Moire

-17-

topography. The measured fringe modulation is zero, and the correct value of the surface modulo C cannot be calculated.

The derivative continuity assumptions of extended-range Moire topography allow the surface to be reconstructed from aliased fringes out to a spatial frequency equal to the MTF cutoff of the pixels. This limit is a factor of 2/G greater than what is obtainable by conventional Moire topography, and gives a limit to the maximum surface slope that can be tested. The power of the extended-range technique now becomes apparent. For example, a 100 by 100 element detector array with G = 0.1 and extended-range processing will have the same fringe "resolution" as a 2000 by 2000 element array processed with conventional Moire topography, but only the data from a 100 by 100 element array must be collected and processed. This example yields a savings of 400 or $(2/G)^2$ in data rates, memory and computations.

It is not possible to predict the maximum surface height that can be measured with an instrument from the maximum surface slope or fringe frequency that it can resolve. However, a factor of 2 change in measurable slope should result in a much larger increase in the measurement range. The amount of curvature that can be measured by the technique of the present invention is much more than a factor of 2/G greater than the measurement range of the standard technique for a detector with the same number of elements.

It is possible, through the application of extended-range Moire topography, to extend the measurement range of existing topography systems. Since the G values of conventional sensors are usually between .5 and 1, an improvement of 2 to 4 in measurable surface curvature is possible through the

method of the present invention, without changing the
hardware of the conventional topography apparatus.

A more intuitive understanding of the
extended-range technique according to the present
invention can be obtained by looking at the process
graphically. The data that is generated by the
phase-shifting operation was shown as the compressed
surface 64 in Fig. 6. Of course, this data only
exists at the sample locations as shown by the sample
values 76 plotted in Fig. 9a. The result of the
measurement however, gives a very precise measure of
the height of the contour modulo C at each sample
location. The actual height will therefore be one of
the solutions to

$$h_i = \tilde{h}_i \pm n_i C \qquad (14)$$

where i indexes the samples, h_i is the correct
height, $\tilde{h}_i$ is the measured height modulo C, and n_i
is an integer. All of these possible solutions are
plotted as points 78 in Fig. 9b. The dotted line 80
represents the original surface used to generate the
data. The surface reconstruction problem can be
thought of as a "connect-the-dots" puzzle where there
are many extra dots. The conventional reconstruction
technique moves from sample to sample and selects the
dot that is closest to the preceding dot. It fails,
of course, when the correct dot is not the closest
dot, i.e. when the surface changes by more than C/2
per sample. This situation is shown by the line
labeled 82 in Fig. 9c where the reconstruction fails
after sample 4. The first derivative continuity
constraint according to the present invention choses
the dot which lies most closely to a line 83 (see
Fig. 9d) connecting the previous two dots. The
correctly reconstructed surface is shown by the line
labeled 84 in Fig. 9d. The reconstruction will fail

when there actually is such a large change of the
surface between samples that the first derivatives
change by more than C/2 per sample per sample.
Similarly, higher order constraints chose the next
5   dot by extropolating a curve that has been fit
through the appropriate number of preceding dots.

As noted previously, the sensor that is
preferred for extended-range Moire topography is one
that has a sparse array of image sensing elements.
10   The most straight-forward way to obtain such a sensor
is to fabricate it. A photolithographically applied
aluminum or opaque mask, which defines the pixel
apertures, may be applied over a standard solid-state
sensor to achieve a sensor with a small value of G.
15   Furthermore, an existing sensor with a high G value
may also be employed. By using every n^{th} sample
produced by such a sensor, an effectively low value
of G is obtained.

As shown in Fig. 1, the computer 33 receives
20   the image from the solid-state sensor 17 and also
provides the signal to control the motion of the
projection grating 18 or an interferometer mirror 32
(see Fig. 2) to implement the phase-shifting
algorithm. The reconstruction of the surface contour
25   of the object is shown on the display 35. The
computer 33 can also be programmed to compare the
measured height profile to a particular design
specification stored in the computer 33 to produce a
pass/fail message on display 35.
30   For implementation of extended-range Moire
topography according to the present invention, an
initial block of samples needed for the starting
point of the reconstruction process must be
identified prior to the start of the reconstruction.
35   This location is chosen manually by the operator by
displaying the Moire pattern on the display 35,
locating an area in the image of the Moire pattern

that has uniform high contrast fringes and inputting
the coordinates to the computer 33 via keyboard 37.
Information about the design of a test part can also
be used to select the starting location within a flat

5   zone on the part. This information may be supplied
to the computer from a CAD/CAM system. Automatic
identification of a starting location is also
possible. For a static fringe pattern, the
sparse-array sensor can be used to scan out the

10 viewed fringe pattern at high resolution by repeated
small translations of the image sensor. The size of
the translations should be on the order of the size
of the pixel aperture. An area in the pattern where
the fringe frequency is in the first Moire interval

15 is chosen as the starting location.

        When two-dimensional data sets are used, the
reconstruction moves outward from the starting
location. An example of a method to accomplish this
process is diagramed in Figs. 10a and b for a

20 starting block 92 of 3 by 3 samples and a second
derivative continuity constraint being applied to the
reconstruction. The three rows of starting samples
are first expanded one row at a time to the right by
the method described below (Fig. 12a) to reconstruct

25 three rows of samples 94. Using a similar procedure,
these three rows are expanded to the left to produce
the reconstructed samples 96 in Fig. 10b. At this
point, three rows of samples across the surface are
completely reconstructed. Three properly

30 reconstructed samples now exist in every column of
samples, and these columns can be individually
reconstructed up and down by an operation that is the
same as the method used for the rows. It should be
clear that other strategies exist for reconstruction

35 of the two-dimensional data set.

        The computer steps needed to implement
extended-range Moire topography according to the

invention are diagramed in Fig. 11. In the first
step 98, the four measurements of the viewed fringe
pattern are made with different phase shifts as noted
in equation (9). At the next step 100, the height of
5   the surface modulo C is calculated as in equation
(11). The block of initial samples to be used for
the reconstruction is then identified (step 102). At
step 104, the height discontinuities are removed by
limiting the height different between samples to a
10   maximum of C/2. The reconstruction to this point is
the same as that produced by the prior art procedure
for Moire topography. Next, the surface constraints
appropriate for extended-range Moire topography are
applied. The slope continuity constraint is applied
15   first, step 106, followed by the second derivative
continuity constraint, step 108. Higher order
continuity constraints can also be applied, (step
110), but simulations have indicated that it is
probably not necessary to implement any constraint
20   higher than second derivative continuity for a sensor
with a G value of about 0.1. The MTF cutoff of the
pixel aperture is reached before this constraint
fails to properly reconstruct a surface contour. For
sensors with lower values of the pixel width-to-pitch
25   ratio G, higher order constraints may provide
improved performance. The final step, 112, is to
display the results.

        Appendix A is a computer program written in
the BASIC language for implementing a
30   first-derivative or slope continuity constraint to a
line of samples. The samples are indexed by N from 0
to Ntotal line 2, HEIGHT(N) line 3 is the calculated
surface height and is initialized with the values
resulting from the standard Moire topography analysis
35   (step 104 in Fig. 11), and SLOPE(N) is the calculated
surface slope. Note that the first sample to be
tested is N=2, or the third sample. Two initial

-22-

samples are needed to start the process. Line 4
tests to see if a slope change of more than C/2 per
sample per sample has occurred. If not, that sample
remains unchanged, and the next sample is tested. If
5   a positive change in slope has been detected (Line
5), C is subtracted from the tested sample and all
subsequent samples (Line 8). This new value of
HEIGHT(N) is retested at Line 4, and the process is
repeated, if necessary. Similarly, C is added to the
10 sample if a large negative slope change is detected
(lines 11-13). The values of HEIGHT(N) that result
from this program will have no large slope changes.
The fact that the program can be written in 15 lines
of code indicates the ease with which this process
15 can be implemented. Analagous steps are used to
implement the second and higher-order derivative
continuity constraints (steps 108, 110 in Fig. 11).
      The extended-range procedure will fail when
the actual surface exceeds the various limits that
20 have been assumed for the derivatives. Fortunately,
since the conditions of failure are known, it is
possible to predict the point at which the
reconstruction becomes invalid. For example, when
the derivative continuity conditions are used, the
25 local values of the slope and higher-order
derivatives are calculated at each sample. As the
calculated values approach the limits in the
assumptions, C/2 per pixel, etc., the reconstruction
is stopped, and a higher-order constraint applied to
30 the data. The calculated value of the slope is used
to determine where the fringe frequency, which is
related to the slope, reaches the resolution limit of
the system -- the pixel MTF cutoff frequency.
      The point at which the viewed fringe
35 frequency reaches the cutoff frequency of the pixel
MTF can also be determined by another method. Up to
this point, the analysis has shown that data from

fringes out to this pixel MTF cutoff frequency can be
analyzed. In practice, there will be some limiting
or threshold MTF below which there will be
insufficient modulation of the recorded fringe
5   pattern to provide reliable estimates of the surface
height. The data modulation at each sample can be
monitored, and any samples failing to meet some
established criteria can be discarded.

Other a priori information about the surface
10   can be used to resolve the surface height
ambiguities. Alternative to or in addition to the
surface smoothness assumptions, it is possible to use
knowledge of the design of a surface having step
discontinuities and abrupt slope changes to remove
15   the ambiguities, if it is known that the design goals
are being met. For surfaces that are known to have
abrupt slope changes, the location of the change
alone may be used to constrain the reconstruction.

Discontinuous Surfaces

20   Moire topography has not generally been
considered a useful technique for measuring surfaces
that have discontinuities or steps larger than half a
contour interval or C/2 in height. This is
especially true for high−accuracy measurements since,
25   for a particular instrument, C also defines the
system resolution. Resolutions on the order of C/100
to C/1000 are commonly achieved. More useful
techniques have been mechanical profilometry or
structured lighting using a single line of
30   illumination. The use of a priori information
according to the present invention makes Moire
topography techniques useful for measuring step
discontinuities.

A Moire fringe pattern 114 for a surface
35   contour having a step 116 running in the horizontal
direction is shown in Fig. 12. The standard Moire
topography measurement gives the step height as a

number between plus or minus a half contour interval, and the actual step height h is

$$h = h_o + nC \qquad (15)$$

where h_o is the measured height, and n is an integer. In Fig. 12, the fringe pattern is shifted by approximately a quarter fringe as would be seen when h_o equals $C/4$.

Information about the step height that has been obtained by another measurement technique, or another source, can be used to resolve the ambiguity in equation (15). This other information must give the height to within less than one contour interval C. The application of this a priori information selects a single value of n, and results in an accurate measurement of the step height. This situation is diagramed in Fig. 13 for a step h. The step height modulo C (h_o) is calculated as a number between $-C/2$ and $C/2$, and the other possible solutions indicated by the points in Fig. 13 are separated by C. The a priori information provides a zone, indicated by cross hatching, of a width C into which only one of these solutions will fall.

As noted above, information that can be used to determine a step height to within less than C may be the part design or parameters describing the manufacturing process. For example, consider a part that has a 25 mm step whose height must be known to within ± 0.005 mm. Conventional Moire topography will be unable to perform this measurement as the chosen contour interval would need to be greater than 50 mm, and the instrument would need to have a resolution of 0.01 mm or $C/5000$. This is an impractical resolution to achieve using conventional techniques. However, if a manufacturing process is used which will produce a step whose height is known to be 25 mm ± 0.1 mm, an extended-range topography system according to the present invention can be

—25—

easily built. This manufacturing tolerance is the total range into which all parts will fall. The standard deviation of the process can be significantly less. A contour interval greater than

5 0.2 mm, for example 0.4 mm, is chosen, and the required measurement resolution of 0.01 mm is then C/40, which is easily obtained. The manufacturing tolerance has been used to define the contour interval, not the step height. The system operates

10 by first measuring the surface height with a standard Moire topography technique. This answer will be in the range —C/2 to C/2 (±0.2 mm). The appropriate number of C's (0.4 mm) are added to this answer until a number between 24.9 mm and 25.1 mm, the

15 manufacturing tolerance, is reached.

        Unlike the case for continuous surfaces, no special sensor configuration is needed to implement extended—range Moire topography on discontinuous surfaces. The power of this technique for this

20 application is that large steps are measured with much smaller contour intervals, while maintaining the resolution inherent to small contour intervals. the only requirements for implementing this technique is that the step height is known a priori to a precision

25 less than one contour interval.

        In a similar manner, the design of the surface can be used in conjunction with known manufacturing tolerances to reconstruct the surface profile of a part that does not comply with the

30 surface derivative continuity constraints. This is illustrated in Fig. 14 in one dimension, where the shaded area 120 represents the total range over which all manufactured parts will fall. It is the part design with a zone to represent the known

35 manufacturing tolerances. This range must be less than a contour interval C wide. It is exactly analogous to the step height range used to determine

−26−

large step heights. The columns of dots 122 are all
of the possible solutions to the surface height at
each sample, as in equation (15), and only one of the
dots in each column will fall into the shaded zone

5   120. These points represent the reconstruction of
the surface at the lateral resolution of the
samples. The precision of the height measurement is
the same as discussed earlier. Changes in surface
height of more than C/2 per sample are allowed by

10 this technique. It is important to note also that if
some segment or portion of the surface is curved,
that segment can be reconstructed by use of the
surface derivative continuity constraints. Each
segment can be handled independently, and different

15 a priori knowledge can be applied to each.

Industrial Applicability and Advantages

        Extended−range Moire contouring according to
the present invention is useful in the industrial
field of surface contour measurement known as Machine

20 Vision. The extended−range Moire contouring
technique is based upon the use of a priori knowledge
about the surface to constrain the reconstruction of
the surface contour. Very simple and reasonable
assumptions, such as the continuity of the various

25 surface derivatives, have been shown to yield
dramatic increases in the measurement range of the
instrument. These new assumptions allow much more
information to be extracted from the data than by
previously available techniques. The advantage that

30 the extended−range technique presents is its ability
to measure large amounts of surface curvature without
resorting to extremely large detector arrays. The
savings is not just in the size of the array, but
also in the data rates, the amount of computer memory

35 and the number of needed computations. The
application of the technique to discontinuous
surfaces provides for a large measurement range with
high precision.

-27-

As mentioned earlier, the data analysis
described is equally well applied to the application
of Moire deflectometry. In this case, what is
measured is the slope of the surface under test, so
5 that the conventional technique applies what is
really a slope continuity condition to the surface.
The extended technique requires that the higher—order
derivatives are also continuous. Once a map of the
surface slope is obtained, the original surface can
10 be deduced. The extension of the technique to
procedures other than phase—shifting Moire
contouring, such as heterodyne Moire contouring will
be immediately apparent to those skilled in the art.

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APPENDIX A

```
 1   SLOPE(1) = HEIGHT(1) − HEIGHT(0)
 2   FOR N = 2 to Ntotal
 3   SLOPE(N) = HEIGHT(N) − HEIGHT(N−1)
 4   IF ABS(SLOPE(N) − SLOPE(N−1)) ≤ C/2, GO TO 15
 5   IF (SLOPE(N) − SLOPE(N−1))>0, GO TO 7
 6   GO TO 11
 7   FOR L = N to Ntotal
 8   HEIGHT(L) = HEIGHT(L) − C
 9   NEXT L
10   GO TO 3
11   FOR L = N to Ntotal
12   HEIGHT(L) = HEIGHT(L) + C
13   NEXT L
14   GO TO 3
15   NEXT N
```

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Claims:

1.   A method of Moire contouring comprising the steps of:

a.   forming a test pattern of lines having
5   distortions representing the contour of a surface;

b.   forming samples of a Moire pattern representing the product of said test pattern and an undistorted reference pattern, said samples representing the height of said contour modulo C,
10   where C is a function of the spacing of the lines of the test pattern;

c.   reconstructing the surface contour from said samples by adding or subtracting multiples of C, characterized in that it includes the step of
15   applying a constraint based on a priori knowledge of the surface to correctly reconstruct the contour when the surface contour changes by more than C/2 per sample.

2.   The method claimed in claim 1, wherein
20   said a priori knowledge of the surface is: 1) that the surface is smooth, therefore, the surface contour being represented by a function having continuous derivatives, and 2) the location of a neighborhood on the surface where the contour changes by less than
25   C/2 per sample.

3.   The method claimed in claim 2, wherein said samples are formed from a sparse array of sampling locations representing a ratio G being less than .5, where $G = a/x_s$, and a is the width of a
30   sample, and x_s is the pitch of samples in the array.

4.   The method claimed in claim 3, wherein $G = .1$.

5.   The method claimed in claim 1, wherein said a priori knowledge of the surface is the
35   location and height of a step discontinuity, the height of the step being known to within less than C.

6.   The method claimed in claim 1, wherein said a priori knowledge of the surface comprises design specifications and manufacturing tolerances.

7.   The method claimed in claim 1, wherein
said Moire contouring method is Moire topography,
said test pattern being formed by projecting a grid
pattern having a period d onto the surface of a

5   diffusely reflecting object, the samples of said
Moire pattern being formed by viewing said surface
with an image sensor having an array of image sensing
elements, and an angle θ from the direction of
projection of said grid pattern, and

10                        $C = d/\tan\theta$.

8.   The method claimed in claim 7, wherein
said Moire topography method is phase-shifting Moire
topography.

9.   The method claimed in claim 8, wherein
15   said test pattern is formed by projecting the image
of a grid.

10.   The method claimed in claim 8, wherein
said test pattern is formed by projecting an
interference pattern.

20   11.   The method claimed in claim 1, wherein
said Moire contouring method is Moire deflectometry,
said test pattern being formed by reflecting a beam
of collimated light from the surface of a specularly
reflecting object and modulating the reflected beam

25   with a grating having a pitch d, the samples of said
Moire pattern being formed by an image sensor having
an array of image sensing elements located a distance
A from the grating, and

                          $C = d/2A$.

30   12.   Moire contouring apparatus comprising:
a.)   means for forming a test pattern of
lines having distortion representing the contour of a
surface;

b.)   means responsive to an image of said
35   test pattern for generating a first signal
representing samples of a Moire pattern formed by the
product of said test pattern and an undistorted

reference pattern, said samples representing the
height of said contour modulo C, where C is a
function of the spacing of said lines in said test
pattern; and characterized in that it further
5   comprises

c.) means for generating a second signal
representing a priori knowledge of the contour of
said surface; and

d.) reconstruction means responsive to said
10 first and second signals for generating a third
signal representing samples of the actual height of
said contour, by adding or subtracting multiples of C
to said samples representing height modulo C, said
actual height samples being correctly reconstructed
15 even when the actual surface contour changes by more
than C/2 per sample.

13. The apparatus claimed in claim 12,
wherein said a priori knowledge of the surface is:
1.) that the surface is smooth, therefore the surface
20 being represented by a function having continuous
derivatives, and 2.) the location of a neighborhood
on the surface where the contour changes by less than
C/2 per sample; and said means for generating said
second signal representing the location of a
25 neighborhood on the surface by less than C/2 per
sample comprises display means for displaying an
image of the Moire pattern, and operator controlled
input means for an operator to input the coordinates
of a neighborhood of the image.

30   14. The apparatus claimed in claim 13,
wherein said means for generating said first signal
comprises a sparse array of image sensing elements
characterized by a ratio G being less than .5 where:

$$G = a/x_s \text{ and}$$

35 a is the width of an image sensing element and x_s
is the pitch of elements in said array.

15. The apparatus claimed in claim 14,
wherein $G = .1$.

16. The apparatus claimed in claim 12, wherein said Moire contouring apparatus comprises apparatus for conducting Moire topography, said means for forming a test pattern comprising means for projecting a fringe pattern having a period d onto the surface of a diffusely reflecting object, said means for generating said first signal comprising an image sensing array arranged to view said surface at an angle θ from the projection axis of said fringe pattern, whereby

$$C = d/\tan\theta.$$

17. The apparatus claimed in claim 16, wherein said Moire topography apparatus comprises apparatus for conducting phase-shifting Moire topography, said means for forming said first signal including means for shifting the phase of said fringe pattern and sampling said Moire pattern three or more times, and means for forming said signal representing height modulo C from said phase-shifted samples.

18. The apparatus claimed in claim 17, wherein said means for projecting a fringe pattern comprises a light source, projection optics, and a grid, and said means for shifting the phase of said fringe pattern comprises means for displacing said grid in a direction perpendicular to the projection axis.

19. The apparatus claimed in claim 17, wherein said means for projecting a fringe pattern comprises a Twyman-Green interferometer having a source of a beam of collimated light, a beamsplitter and a pair of plane mirrors, and the means for shifting the phase of said fringe pattern comprises means for displacing one of said mirrors parallel to the collimated light beam.

20. The apparatus claimed in claim 12, wherein said Moire contouring apparatus comprises apparatus for conducting Moire deflectometry, said

—33—

means for forming a test pattern comprising means for
shining a beam of collimated light onto the surface
of a specularly reflecting object, a grating having a
pitch d for modulating the reflected beam, and an
image sensor having an array of image sensing
elements located a distance A from the grating, and

$$C = d/2A.$$

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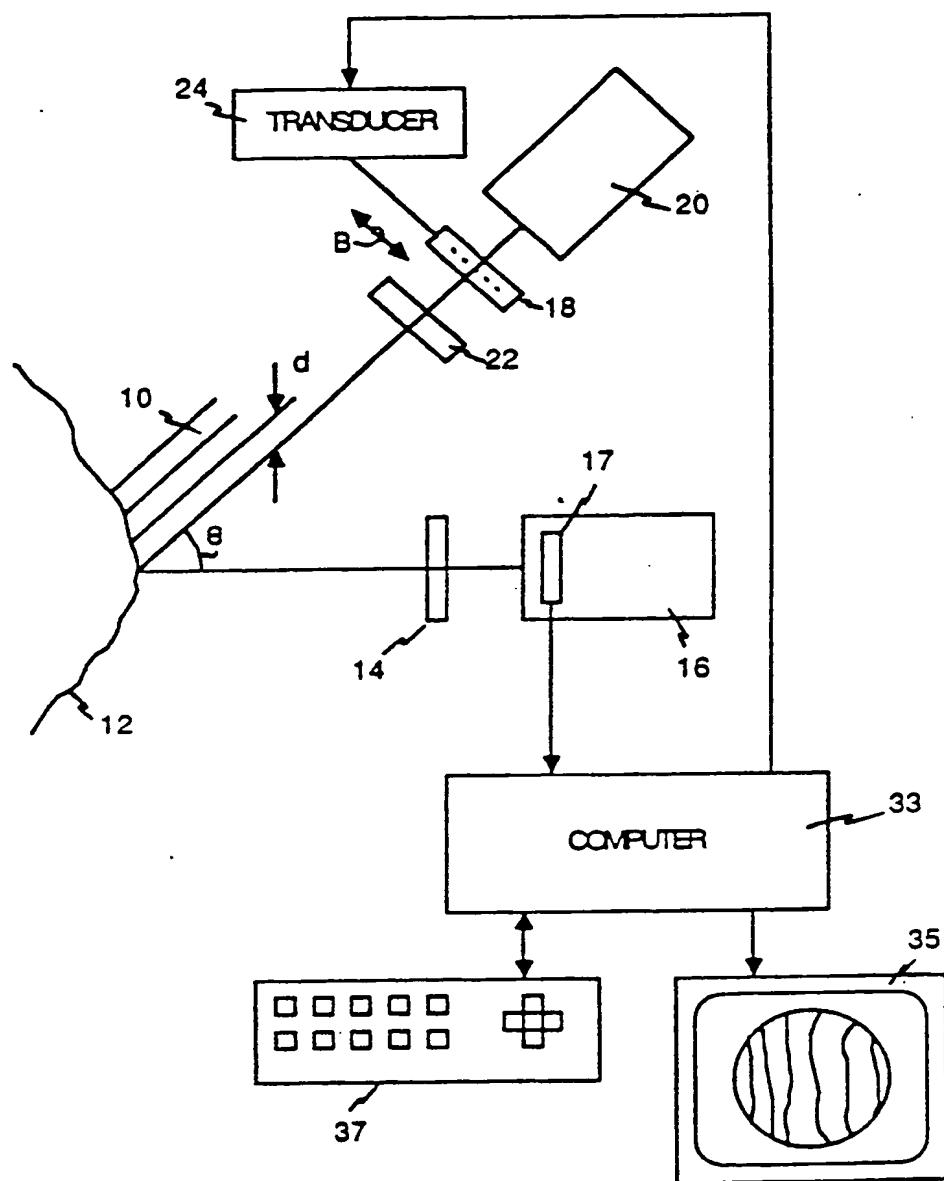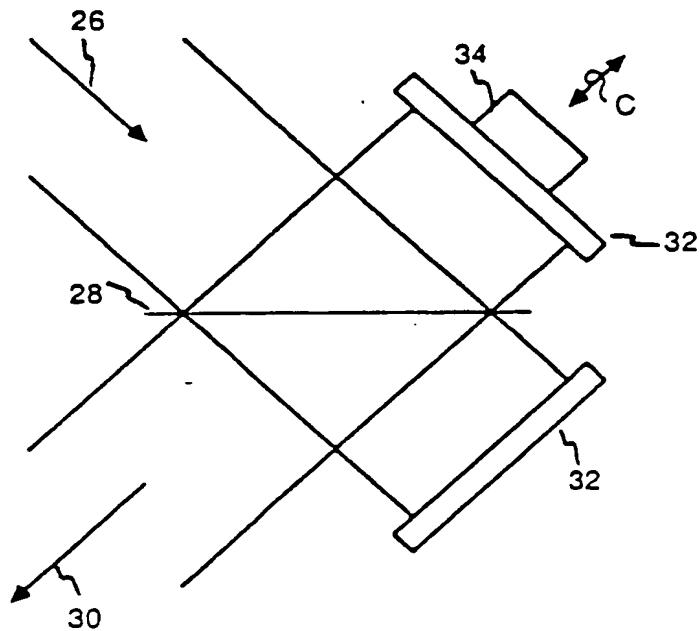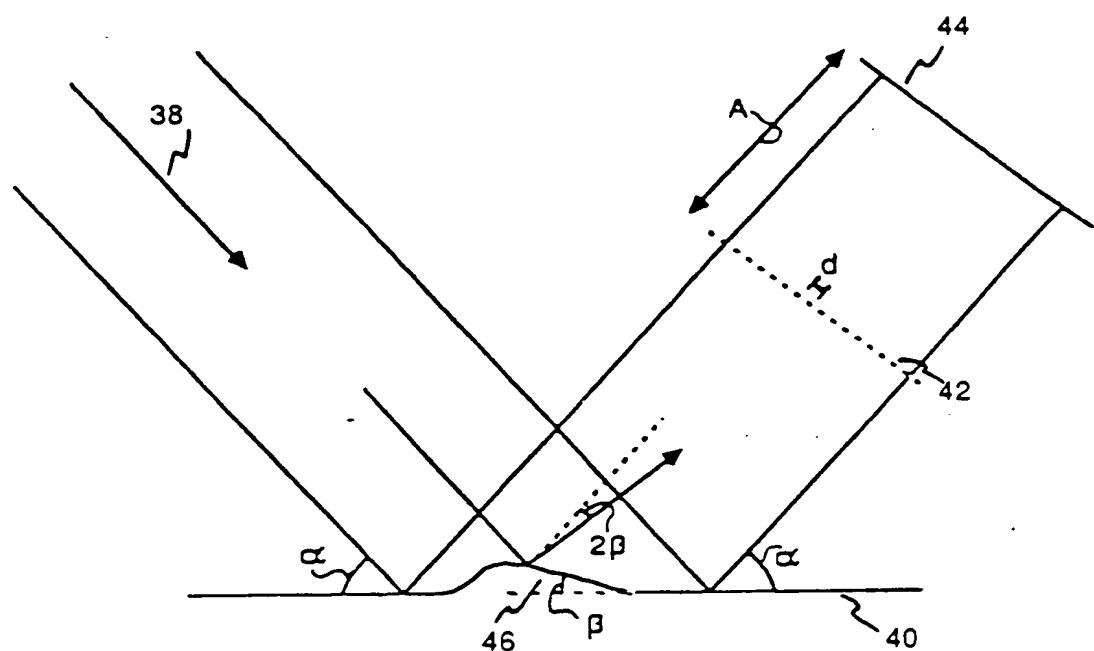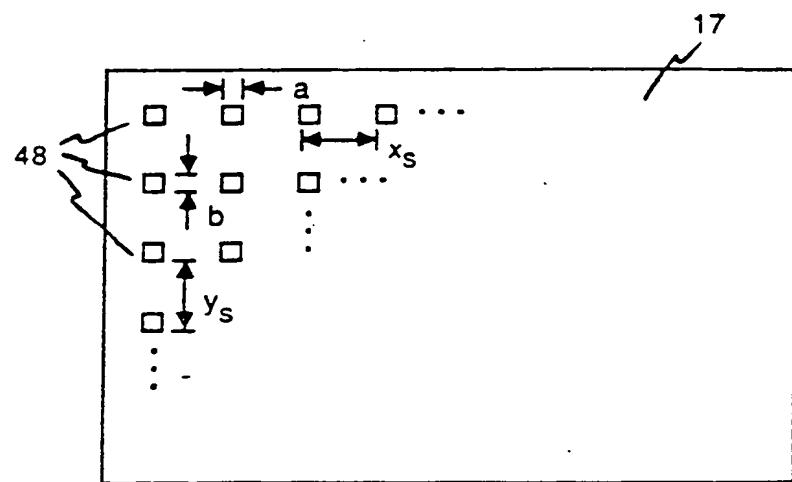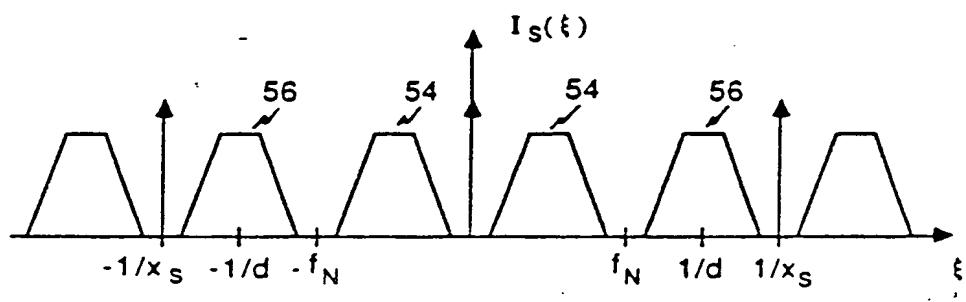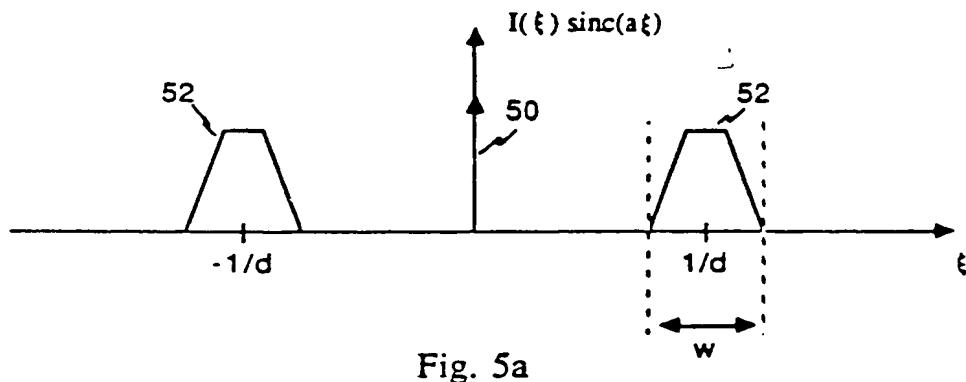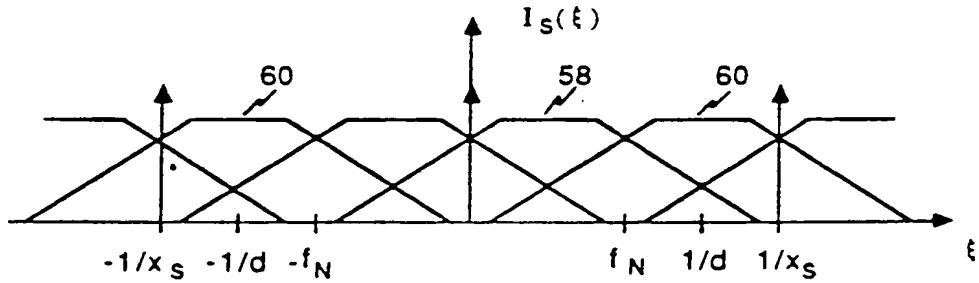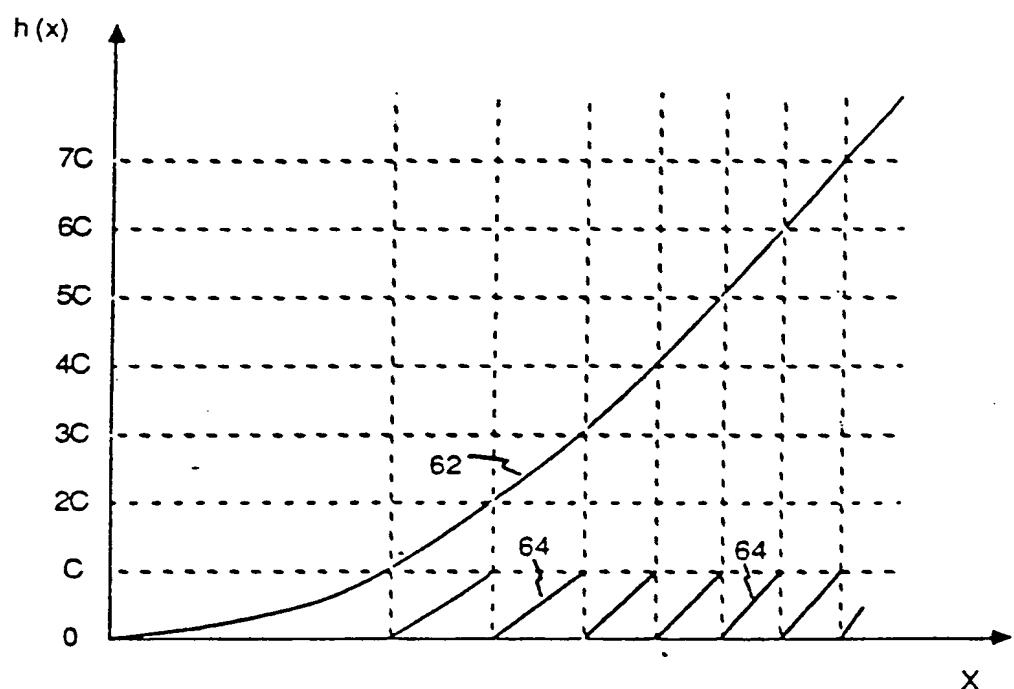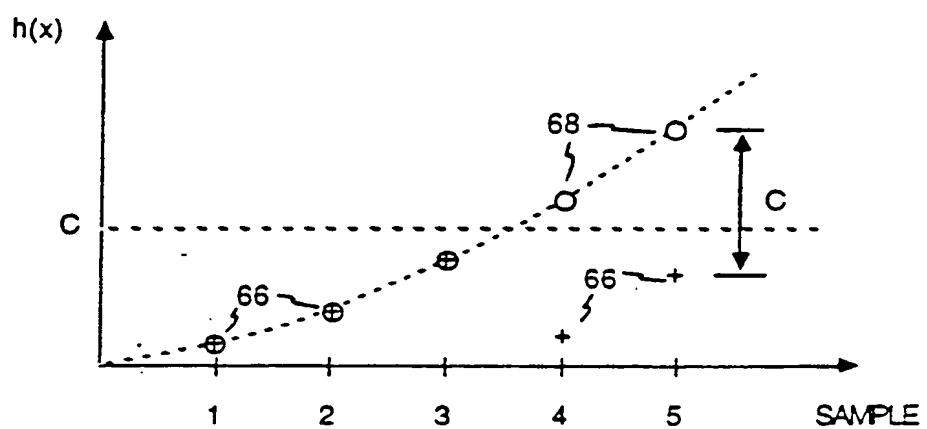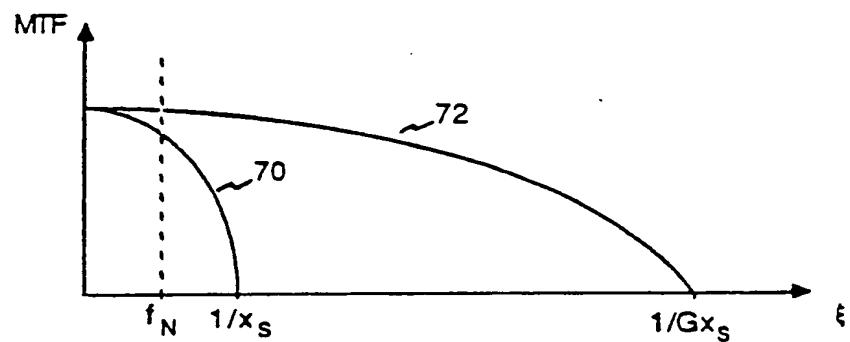
Fig. 1

Fig. 2

Fig. 3

4/17

Fig. 4

Fig. 5a

Fig. 5b

Fig. 5c

Fig. 6

Fig. 7

Fig. 8

Fig. 9a

Fig. 9b

Fig. 9c

Fig. 9d

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□　　□　　□→▨　▨　▨ · · ·

□　　□　　□→▨　▨　▨ · · ·

□　　□　　□→▨　▨　▨ · · ·

└────────┘└──────────────┘
　　　　92　　　　　　94

Fig. 10a

· · ▨　▨　▨←□　□　□　□　□　□ · · ·

· · ▨　▨　▨←□　□　□　□　□　□ · · ·

· · ▨　▨　▨←□　□　□　□　□　□ · · ·

└──────────────┘└──────────────┘
　　　　96　　　　　　　92

Fig. 10b

START

98 — Record Data:
-step phase shift
-record and store intensity pattern
-repeat for four steps

100 — Calculate surface height profile
modulo C at each sample - Eq. (11)

102 — Identify initial block of samples

104 — Apply standard Moire topography analysis
to remove discontinuities
(surface continuity constraint)

106 — Apply slope continuity constraints
to data at each sample

108 — Apply second derivative continuity
constraints to data at each sample

110 — Apply higher-order constraints if needed

112 — Display Results
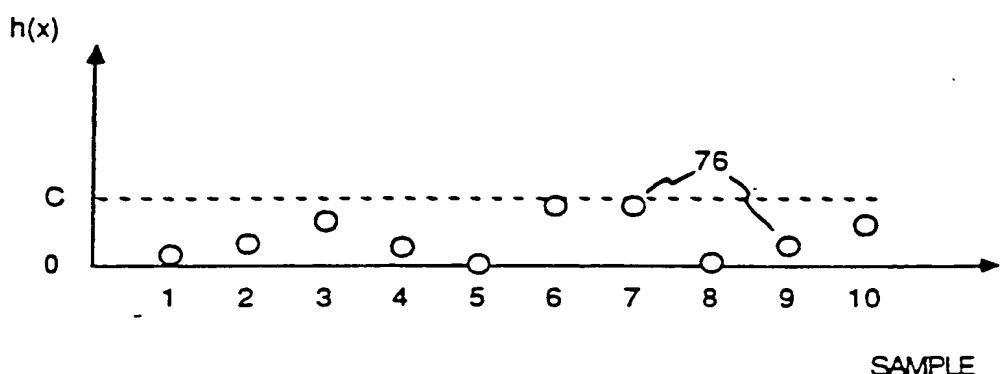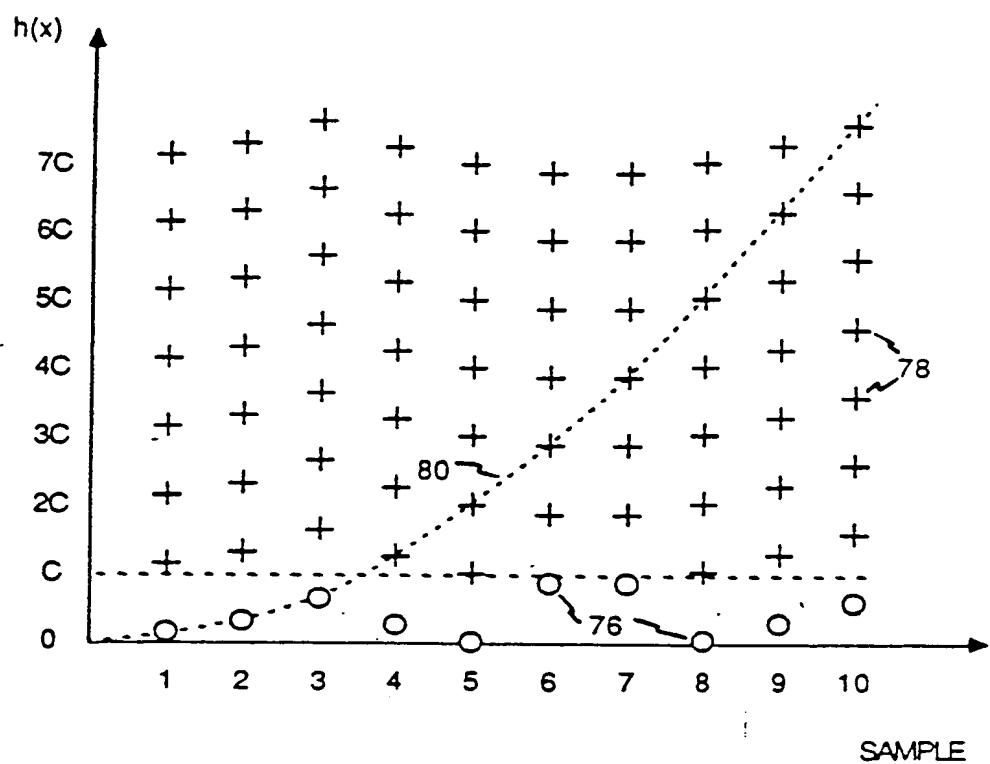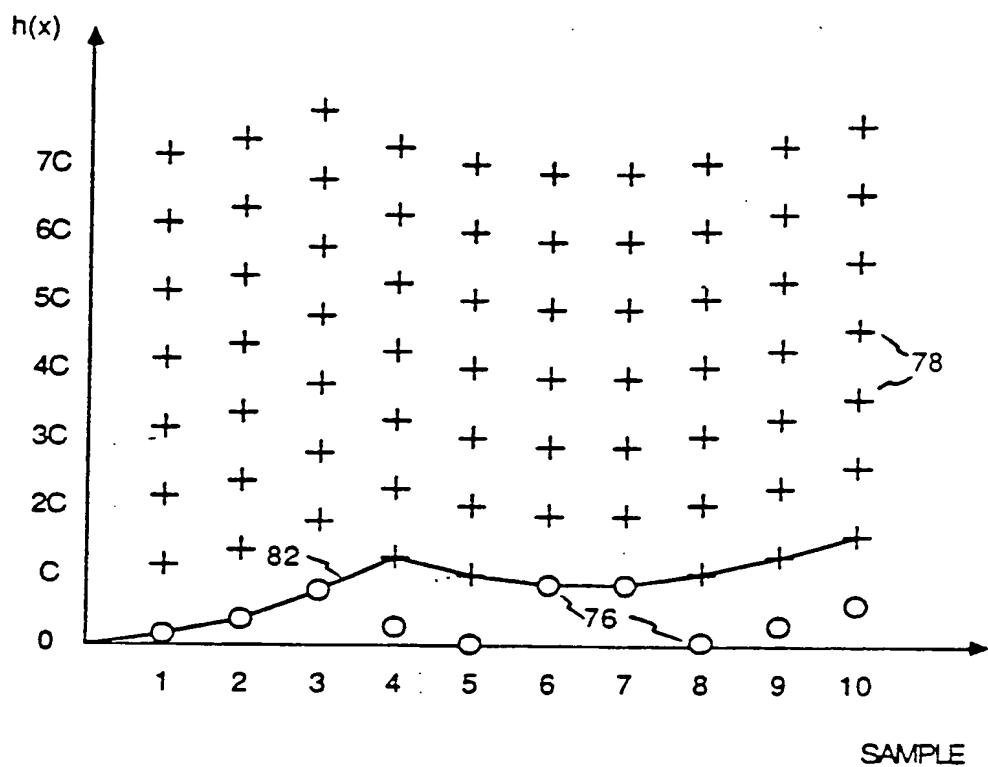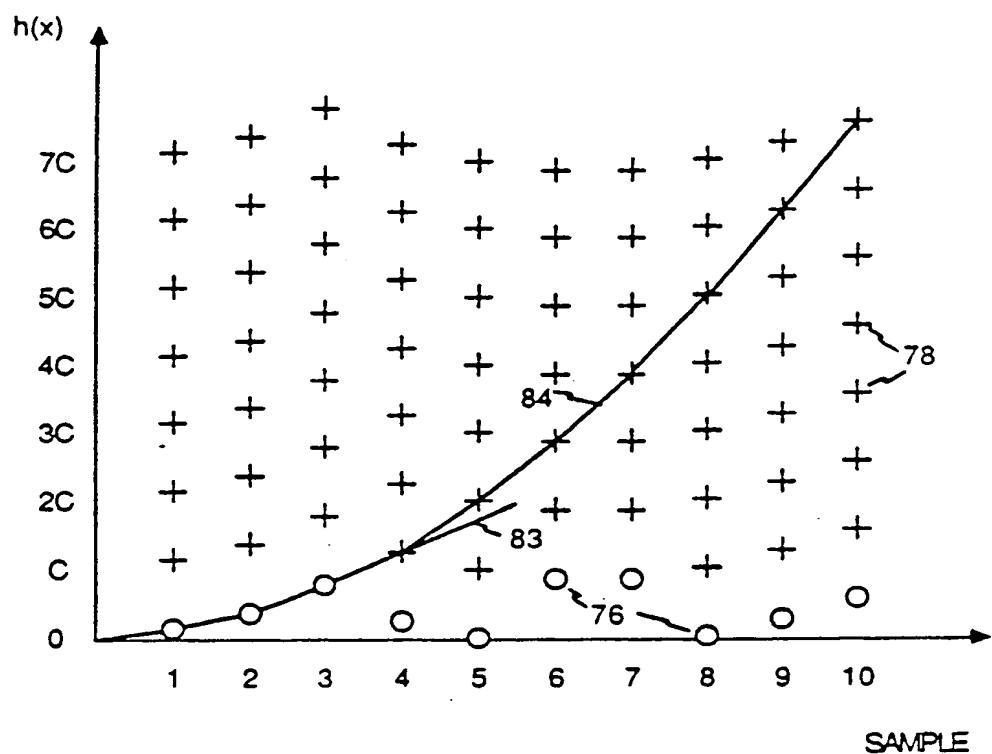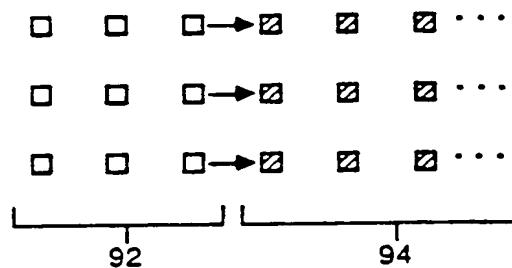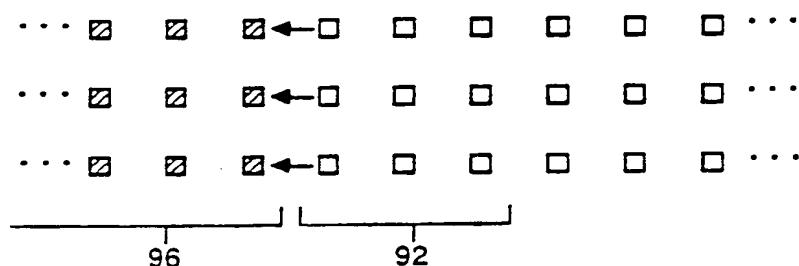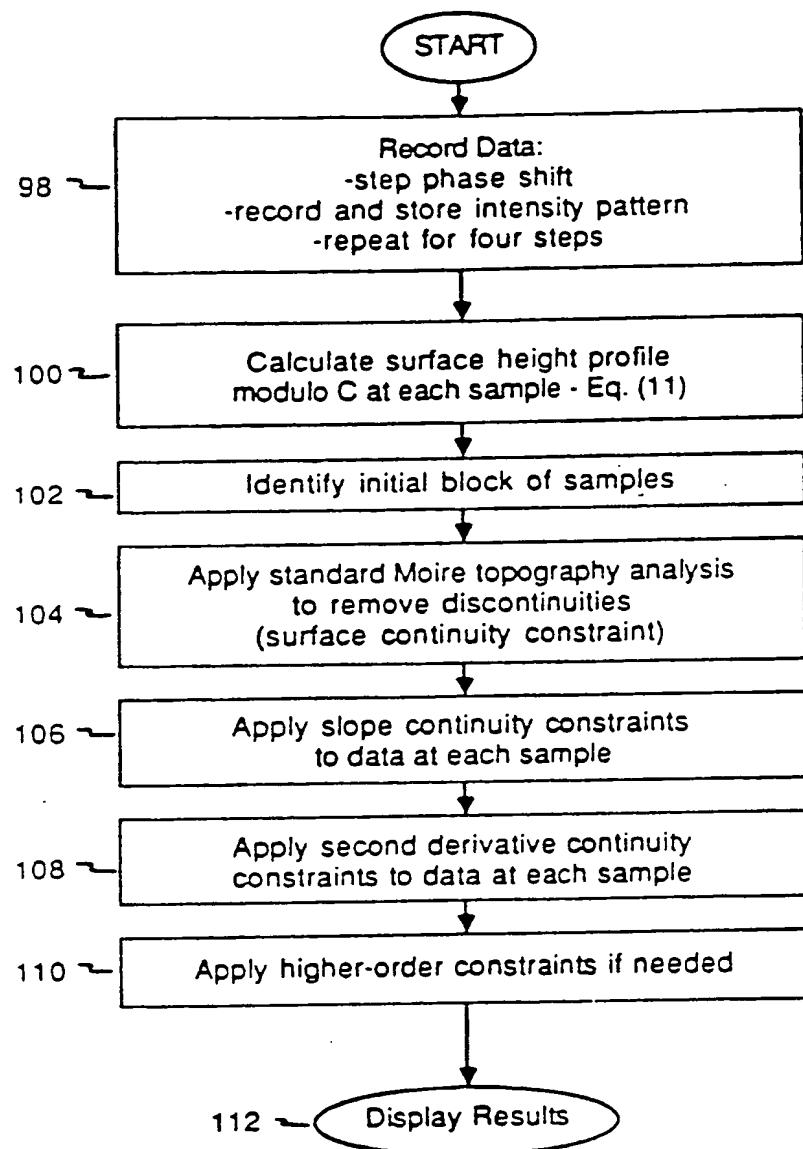
Fig. 11
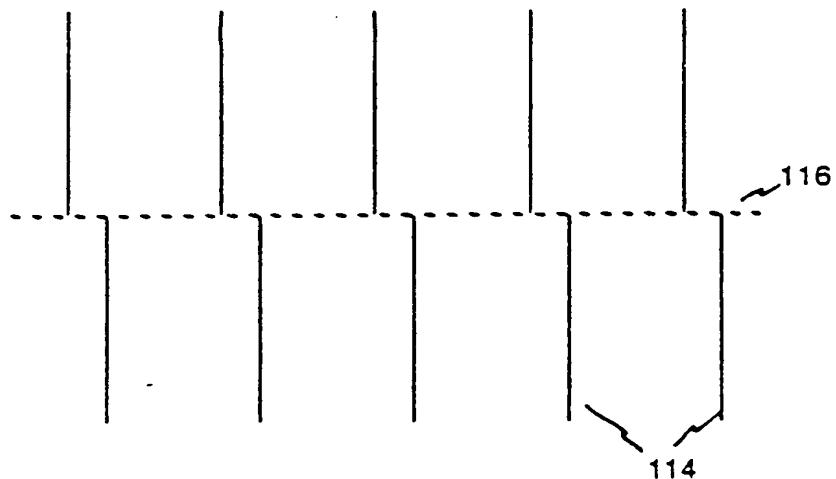
Fig. 12
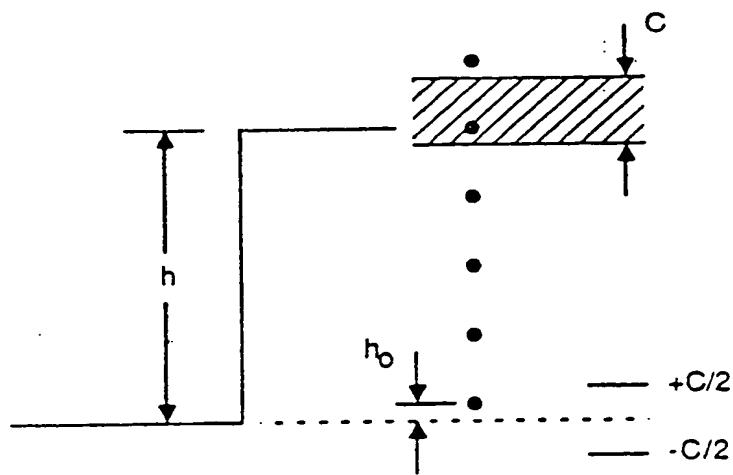
Fig. 13
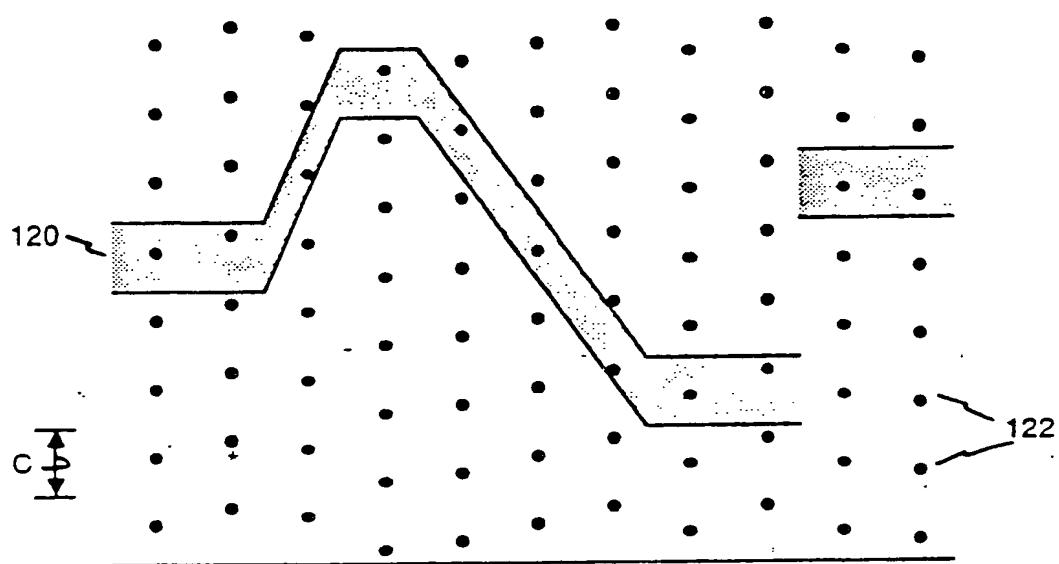
Fig. 14

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification [4] : **G01B 11/24**	**A3**	**(11) International Publication Number:** **WO 88/02847** **(43) International Publication Date:** 21 April 1988 (21.04.88)

(54) Title: EXTENDED-RANGE MOIRE CONTOURING

(57) Abstract

The measurement range of Moire contouring techniques is extended beyond the Nyquist frequency limit by constraining the reconstruction of a surface contour according to a priori knowledge about the surface. In one example, the a priori knowledge is that the surface is smooth, being described by a function having continuous derivatives, and the location of a region where the surface changes by less than C/2 per sample. In another example, the a priori knowledge is the location and height of a step discontinuity to within C/2, where C is the contour interval.

INTERNATIONAL SEARCH REPORT

International Application No **PCT/US 87/02563**

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) *

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC⁴: G 01 B 11/24

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
IPC⁴	G 01 B

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with Indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	EP, A, 0182469 (NEW YORK INSTITUTE OF TECHNOLOGY) 28 May 1986 see introduction, figures 1-9; page 12, line 1 - page 22, paragraph 1; page 22, paragraph 2 - page 28, paragraph 1; figures 10-23; page 28, paragraph 3 - page 38, paragraph 1	1,5-12, 16-20
X	Applied Optics, volume 24, no. 2, January 1985, Optical Society of America, (New York, US), V. Srinivasan et al.: "Automated phase-measuring profilometry: a phase mapping approach", pages 185-188 see pages 185-188	1,2,5-13, 16-20
A	US, A, 4452534 (D.D. GRIBANOV et al.) 5 June 1984 see figures 1-4,8; column 7, line 25 - column 10, line 34; column 12, line 12 - column 13, line 63	1,8,10-12, 16,17,19

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* Special categories of cited documents: [10]
"A" document defining the general state of the art which is not considered to be of particular relevance
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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
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IV. CERTIFICATION

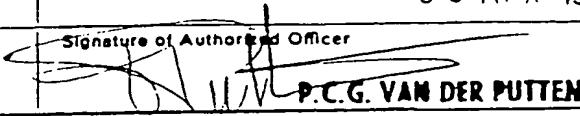| Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
22nd February 1988	0 8 APR 1988

International Searching Authority	Signature of Authorized Officer
EUROPEAN PATENT OFFICE	P.C.G. VAN DER PUTTEN

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This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on 21/03/88
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Patent document cited in search report	Publication date	Patent family member(s)		Publication date
EP-A- 0182469	28-05-86	JP-A- US-A- US-A-	61076906 4641972 4657394	19-04-86 10-02-87 14-04-87
US-A- 4452534	05-06-84	FR-A,B DE-A-	2513371 3138161	25-03-83 14-04-83

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